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TECHNOLOGY DEVELOPMENTS FOR A COMPOUND CYCLE ENGINE

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SUMMARY

The Compound Cycle Engine (CCE) is a highly turbocharged, power compounded power plant which combines the lightweight pressure rise capability of a gas turbine with the high efficiency of a diesel. When optimized for a rotorcraft, the CCE will reduce fuel burned for a typical 2 hour (plus 30 min reserve) mission by 30 to 40 percent when compared to a conventional advanced technology gas turbine. The CCE can provide a 50 percent increase in range-payload product on this mission.

Results of recent activities in a program to establish the technology base for a Compound Cycle Engine are presented. The objective of this program is to research and develop those critical technologies which are necessary for the demonstration of a multicylinder diesel core in the early 1990's. A major accomplishment has been the initial screening and identification of a lubricant which has potential for meeting the material wear rate limits of the application.

An in-situ wear measurement system has also been developed to provide accurate, readily obtainable, real time measurements of ring and liner wear. Wear data, from early single cylinder engine tests, are presented to show correlation of the in-situ measurements and the system's utility in determining parametric wear trends.

The paper concludes with a plan to demonstrate a compound cycle engine by the mid 1990's.

INTRODUCTION

A program is being conducted to develop those technologies critical to demonstrating a 2000 hour mean time between overhauls, MTBO, high specific power, light weight compound cycle engine (CCE). Recent studies have shown that fuel is 70 percent of the tonnage shipped by the Army for supply and

support under battlefield conditions. Another study (ref. 1), showed that a compound cycle engine, with its superior fuel efficiency, when installed in a Blackhawk helicopter and operated over a typical 2-hour mission, could have a specific weight as high as 0.76 pound per horsepower (lb/hp) and still be competitive with a gas turbine engine in terms of range-payload product. This result assumed the same take-off gross weight, and balanced the CCE's increased engine weight against its lower fuel consumed plus tankage weight.

This paper summarizes the activities and results to date under this technology development program. The major part of these activities is being conducted by the Garrett Turbine Engine Company, under the sponsorship of the U.S. Army Aviation Systems Command (AVSCOM). The efforts include an analytical feasibility study of a compound cycle engine for a light helicopter application; a lubricant and material research and development program; and a component technology development program. The paper will conclude with a long range plan to meet a 1990's multicylinder diesel core demonstration date.

BACKGROUND

A comparison of the performance of small to medium size shaft power engines (200 to 6000 hp), shows the potential for reduced fuel consumption with the incorporation of a diesel or compound cycle power plant (fig. 1.). The greatest fuel savings come from the use of a compound cycle, which is also the lighter of these two options.

The compound cycle engine, shown schematically in figure 2, combines the airflow capacity and light-weight pressure rise features of a gas turbine with the highly efficient, although heavier, diesel. The compressor of the turbomachinery module delivers a highly pressurized charge of air to the diesel cylinders. Within the cylinders, further compression, fuel injection, combustion, and expansion takes place, as in any conventional reciprocating engine, but at substantially higher pressures and temperatures. Power is extracted during the expansion stroke and the exhaust gases are then returned to the turbomachinery module. The exhaust energy available is in excess of what is required to drive the compressor, and that excess power is extracted in a free turbine and combined with the diesel output through a gear train. This combined output comprises the total cycle output, hence the name compound cycle engine.

As outlined in reference 2, the 1940's and early 1950's saw considerable interest in compound cycle engines being applied to aircraft. During the early 1950's, the most fuel efficient internal combustion engine ever flown, the Napier Nomad, demonstrated an SFC of less than 0.35 lb/hp-hr in flight (ref. 3). The engine used a highly turbocharged, power compounded cycle to reach this level of performance. It delivered 3050 hp output at a weight of 3580 lb. The advent of the gas turbine, however, coupled with the low cost of fuel at the time and the drive toward faster speeds, brought an end to the Nomad. This technology stagnated while gas turbines flourished in the 30-plus intervening years. As figure 3 indicates, the performance of small simple cycle gas turbines is now at a level where further improvement in specific fuel consumption is very difficult to achieve due to the high pressure ratios that would be required. In addition, to produce a smaller package than presently in production for a given power class of engine, would require higher

turbine-inlet temperatures than either materials, cooling, or manufacturing technologies are ready to deal with.

The Army/NASA Small Engine Technology program (ref. 4), indicated that performance increases of significant magnitude for the year 2000 turbomachine will require improved cycles incorporating the results of intensive research and development efforts in: (1) materials, i.e., ceramics for higher cycle temperatures, and (2) in component aerodynamic design for improved efficiencies. Efforts in other areas will provide payoffs of a smaller magnitude. The reduction in fuel burned predicted for the year 2000 rotorcraft application was dependent on all the key technologies reaching the applications phase (refs. 5 and 6).

Economic and logistic pressures have forced us to reconsider other, more efficient power plants such as the compound cycle. The already mentioned tonnage which the Army must supply and support under battlefield conditions, and the need for a deep penetration capability, are examples of the drivers toward better fuel efficiency. It is estimated that by adapting the Napier Nomad to a helicopter mission and incorporating modern technologies into its 35 year old design, this compound cycle engine could be made to run at an SFC in the range of 0.35 lb/hp-hr and weigh 0.6 lb/hp or less. The weight reduction would be accomplished by removing the reduction gearbox, which had been needed for a propeller drive, and deleting the variable-speed transmission, which had been needed for turbomachinery and diesel speed matching. Instead a free turbine stage would be used for power extraction and the number of turbomachinery stages reduced substantially from the original Nomad design. Modern materials and structural analysis techniques would also be employed

Until recently, few major advances have occurred in reciprocating engines. In 1977, however, a joint Defense Advanced Research Project Agency (DARPA), Air Force program, the Compound Cycle Turbofan Engine (CCTE) of reference 7 at Garrett, investigated a highly turbocharged, power compounded turbofan/diesel engine for a cruise missile application. Power densities greater than seven times that of the best current production diesels were demonstrated in a single cylinder rig. A mission redirection terminated that effort. However, that program formed the basis for the present activity.

COMPOUND CYCLE ENGINE PROGRAM

The goal of the compound cycle engine (CCE) program is a 30 to 40 percent reduction in mission fuel weight with a resultant 50 percent improvement in payload-range product for a light helicopter. The program objective is to demonstrate the low specific fuel consumption and low specific weight potential of a compound cycle turbine-diesel engine for a light helicopter application. The immediate activity is focused on those technologies which are critical to the demonstration of a high specific power, long life (2000 hr mean time between overhauls, MTBO), light weight multicylinder diesel core in the early 1990's. Toward this end, the Garrett Turbine Engine Company has been under contract since 1984 to perform a technology research and technology development program. The contracted activity includes a feasibility study to determine the merit of using a CCE in a dual, 1000 hp engine, light helicopter; lubricant and material research and development; and single cylinder component research.

Light Rotorcraft Feasibility Study

A thorough review of the feasibility study is presented in reference 2. Selected highlights of the results are presented here, to preface the technology development discussion.

The final engine design (fig. 4), is quite similar to a free turbine turboshaft engine, but with the combustor replaced by a power producing six cylinder diesel core operating on a uniflow scavenged, 2-stroke cycle. A two stage centrifugal compressor raises the charge air pressure to 10.6 atmospheres. This air then passes through an air-to-air aftercooler which lowers its temperature (increases density) prior to it being inducted into the cylinders through circumferential ports at the bottom of the piston stroke. The air is compressed to 1/7.5 times its original volume on the upward stroke of the piston and fuel is injected near top dead center, burned, and exhausted through valves in the head on the piston down (power) stroke. The engine exhaust gases then flow through the single-stage, radial-inflow gas generator turbine which drives the compressor. The exhaust then flows through the axial flow free power turbine which puts power back into the diesel crankshaft through gearing. A cutaway of a generic installation is shown in figure 4.

Table I provides a list of selected design point parameters for the CCE and for current production heavy duty diesels. The comparatively low weight of the CCE is achieved, to a large extent, by doing the majority of the cycle pressure rise through compression in the turbomachinery. The CCE's high power density results from a combination of the 2-stroke cycle, high engine speed, high cylinder pressures and small piston displacement.

The study indicated that substantial fuel savings and improvements in range-payload product are potentially available with the CCE. For a representative mission of 2 hours (plus 30 min reserve fuel) during which 80 percent of the time is spent at or below 50 percent power, the CCE propulsion system plus fuel and tankage weight equalled that of a gas turbine in less than one hour. Beyond this time the CCE system became progressively lighter than a gas turbine. This result arises from the lower specific fuel consumption of the CCE; 25 percent better than a current development gas turbine at design power, and improving to 36 percent better at 50 percent power, as shown in figure 5.

The study identified three critical technology development areas: piston ring/liner interface wear life; exhaust valve temperatures; and rapid fuel injection with high heat release combustion. Since the completion of the feasibility study and with identification of the critical technologies, program activity has concentrated on the major challenge to meeting the high power density 2000 hour MTBO goal. This challenge is the low piston ring/liner interface wear at high speed and power densities. The wear is investigated in the lubricant/material screening, and in the single cylinder engine testing. The following sections of this report discuss the screening and engine testing activities and progress to date.

Lubricant/Material Screening

The objectives of this effort are to: identify a lubricant that is compatible with the critical environment and requirements of the diesel and gas turbine engines; and identify potential diesel engine piston ring/cylinder liner material and lubricant combinations. Lubricants and materials are being screened on a modified Hohman friction and wear tester (fig. 6). Two rub blocks wear against a rotating shaft under simulated cylinder pressure, velocity and temperature conditions (P, V, T).

This activity began with the best tribological combination from the DARPA/Air Force program of reference 7 as a baseline. This combination was Koppers K-1008 (Cr_2C_3-Moly) coated blocks (simulating a piston ring) rubbing on an N-135 (Nitralloy) Nitrided shaft (simulation a cylinder liner), and lubricated with Stauffer STL + 10 percent TAP. The lubricant approach is to use gas turbine type of lubricant basestocks and modify them to meet diesel requirements. This activity is underway and will be followed by tests of potential piston ring/cylinder liner hard wear resistant material combinations with the most promising lubricant. The best lubricant to date has been Monsanto MCS-2189 (MIL-L-27502 type) which reduced the wear rate to 1/7 of baseline level, and the friction coefficient (0.016 avg.) and frictional temperature rise (205° F avg.) at 800° F to 60 percent of their baseline levels. Additives are also being tested with MCS-2189.

While the systematic approach used in screening lubricant and material combinations has provided promise of approaching the TBO goal, there is a need to extend the qualitative screening activity to a quantitative understanding of the dependence of wear on the cycle parameters of cylinder pressure and temperature and piston velocity, on the tribology of the system, and on the overall engine operation. Figure 7 depicts the interrelationship of in-cylinder operational parameters. Although the parameters are being varied, no attempt is being made to develop a correlation between the parameters.

Single Cylinder Engine Testing

The overall objective of the single cylinder engine testing is to demonstrate single cylinder diesel component life and performance in preparation for the multicylinder diesel core engine demonstrator program. This activity is presently concentrating on in-cylinder piston ring/liner wear and tribology. It began by using hardware from the DARPA-Air Force program in which the single cylinder engines had been run at more than seven times the power density of the best current production diesels, reaching 7.2 hp/cu.in. These engines, although loop scavenged, provided an early opportunity to concentrate on piston ring/liner wear while operating at the specific power levels of the CCE. It should be noted that during the single cyclinder engine tests, power densities of nearly 5 hp/cu-in were consistently obtained in over 100 hours of testing.

The present program piston ring/liner wear activity has dealt mainly with the development of a method for making in-situ, real time measurements of wear. These measurements are obtained using a SPIRE-WEAR radionuclides measurement system (ref. 8), which has been developed to a point of relatively

good utility and accuracy. Data using this system were used to establish baseline wear rate measurements.

Figure 8 is a representation of how the radionuclide system works. Hardware, in this example a piston ring, is irradiated by exposing the wear surface to an accelerator particle beam. Careful control over the bombardment parameters results in a desirable distribution and level of activity in the surface of the ring. The ring is then subjected to wear in an engine under controlled conditions of P, V, T. The ring activity is measured through the top of the cylinder by a scintillation counter and is continuously recorded for computer analysis. The activity history is compared against the known radioactivity distribution, corrected to account for normal isotope decay, to provide a history of wear versus time. The wear rate of change is then correlated with the test P, V, T conditions. The discussion in reference 8 provides more detail on this method of wear measurement. Those items that required special attention for use in the single cylinder engine rig are mentioned below.

Development of the wear measurement system required identification of an appropriate material/isotope combination to provide a reasonable energy level and half life to accomplish wear rate test objectives. Location of the radiation detector for optimum data acquisition, and maintenance of a constant detector temperature were key to achieving consistent results. Software modifications included changing the energy integration technique to an area integration scheme over a wider bandwidth than originally proposed. This allowed faster, more accurate acquisition of data. As a result, the SPIRE-WEAR system and test setup was ready to be applied on the next test sequence which will utilize a uniflow scavenged engine, modified to operate as a single cylinder test rig.

Figure 9 shows representative ring wear data recorded over 15 nonconsecutive test hours of operation on the single cylinder, loop scavenged engine test rig. All the running was at a speed of 6000 rpm with a cylinder inlet temperature of 300° F, and with the baseline tribological combination. The data from the first 4 1/2 hours were recorded at an inappropriate sample rate and therefore reliable wear rate calculations were not possible. From 4 1/2 hours on, a more optimum sampling was used, and it can be seen that the wear rate (slope of the line) is quite repeatable for repetitions of the same power level: 0.6 μm/hr at 40 IHP, 0.7 to 1 μm/hr at 60 IHP, and 2.0 μm/hr at 80 IHP. These wear rates when projected onto the composite helicopter mission profile, and allowing a 0.006 inch allowable radial ring wear, indicate a 200 hour TBO (time between overhauls) with the baseline materials and lubricant in a loop scavenged engine. Projecting the improvement of using Monsanto MCS-2189 into the uniflow scavenged single cylinder engine, a 1400 hour TBO life would be anticipated.

The set of data shown in figure 9 also provided one check on the accuracy of the measurement system. The calculated wear over 15 hours of operation was 22.7 μm, while the actual measured wear was 25 μm, indicating an overall difference of about 10 percent. The percentage difference was greater on some of the other tests. A nominal value of uncertainty has not yet been determined.

Figure 10 provides an indication of the capability afforded with the in-cylinder wear measurement. It represents over 20 data points recorded in

slightly less than 31 non-consecutive test hours with a single activated ring, run on one build of the engine. Using standard, intrusive types of measurements would have required at least twenty partial disassembly/assembly operations, introducing substantial doubt about the configuration repeatability. The wear data was acquired on the loop scavenged configuration, and is therefore not quite representative of the uniflow scavenged design. However, it does demonstrate that the radionuclides system provides the capability to perform the type of parametric studies of ring wear rate versus cycle parameters and cylinder tribology that were indicated by figure 7. As the uniflow scavenged single cylinder activity approaches the power levels of the CCE, actual configuration wear rate parametric relationships should begin to emerge.

COMPOUND CYCLE ENGINE PROGRAM PLAN

The CCE program plan is presented in figure 11. As shown, the component technology activities have been ongoing since late 1984, these being mainly the lubricant/wear (tribology) and single cylinder research under contract to the Garrett Turbine Engine Company. The immediate objective of these activities is to demonstrate that we know how to meet the 2000 hour MTBO goal. In addition, it is necessary to develop the critical technologies required for the demonstration of a high specific power, light-weight multicylinder diesel core in the early 1990's. The diesel core engine (gas generator) demonstration would lead into a full CCE demonstrator by the mid 90's. It is anticipated that the component technologies effort would continue through the entire program, with specific tasks changing as requirements arose. To meet the overall program timeframe, progress in the component technologies must continue

SUMMARY OF RESULTS

Studies have shown that a compound cycle turbine diesel engine is an advanced engine concept which has potentially high benefits for the Army light helicopter application. These benefits include a 30 to 40 percent reduction in fuel burned and a 50 percent increase in payload-range product for a dual-1000 hp engine helicopter on a 2 hour (plus 30 minute reserve fuel) mission.

Early tribological screening and single cylinder engine tests indicate that good progress is being made toward obtaining the 2000 hour MTBO life goal. It is expected that continued progress will be made in the development of improved lubricants such as Monsanto MCS 2189, with equal success in material optimization, in order to reach utility in time for use in the CCE program.

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TABLE I. - COMPARISONS OF DESIGN PARAMETERS FROM 1000 HP HELICOPTER ENGINE STUDY WITH CURRENT DESIGN PRACTICE

Parameter	Target	Current design practice
$P/P_{compressor}$	10.6	2 - 3
Comp. ratio	7.5	14 - 17
Diesel speed	6000 rpm	1800 - 2500 rpm
Top ring reversal temperature	800 °F	<450 °F
Brake mean effective pressure	393 psi	150 - 250 psi
Mean piston speed	3000 fpm	<2000 fpm
lbm/hp	0.432	5 - 10
hp/in^3	5.7	0.5 - 1

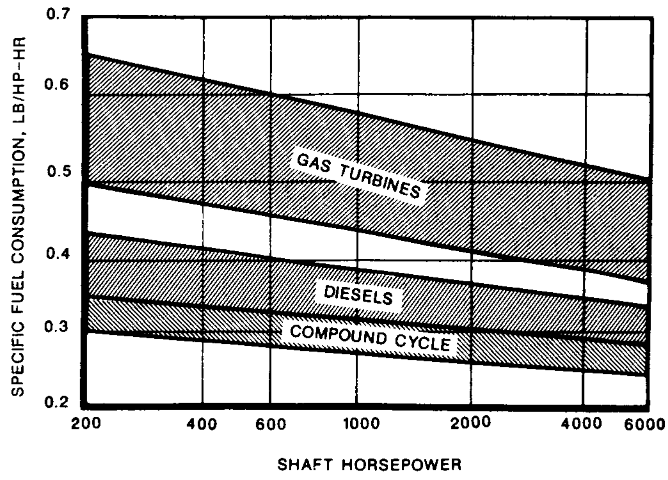

FIGURE 1. - GENERAL PERFORMANCE COMPARISON OF SHAFT-POWER ENGINES (200-6000 HP).

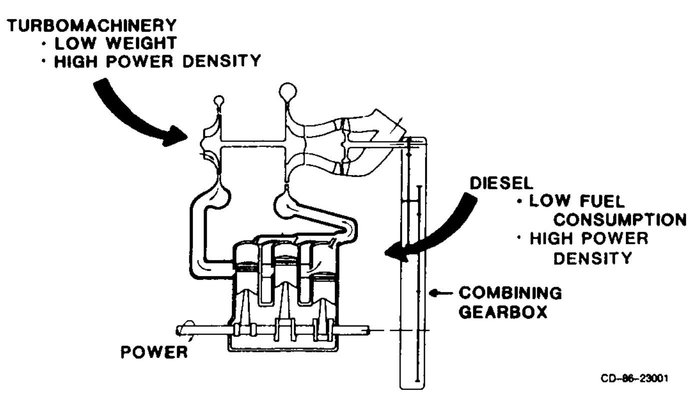

FIGURE 2. - SCHEMATIC OF A COMPOUND CYCLE ENGINE.

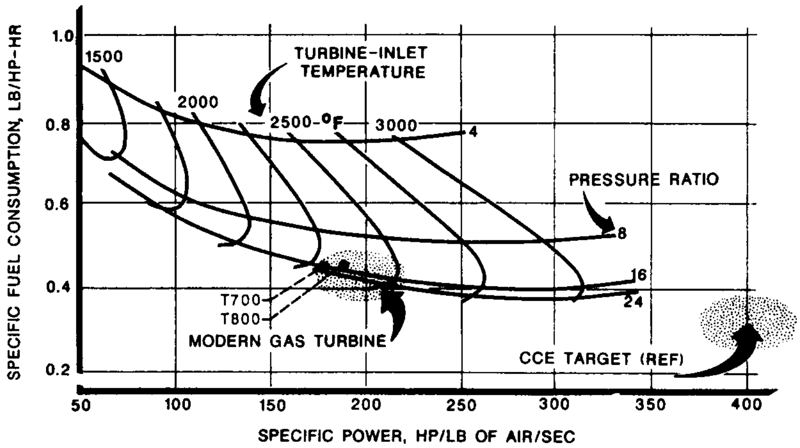

FIGURE 3. - GAS TURBINE ENGINE PERFORMANCE DEPENDANCE ON PRESSURE RATIO AND TURBINE-INLET TEMPERATURE.

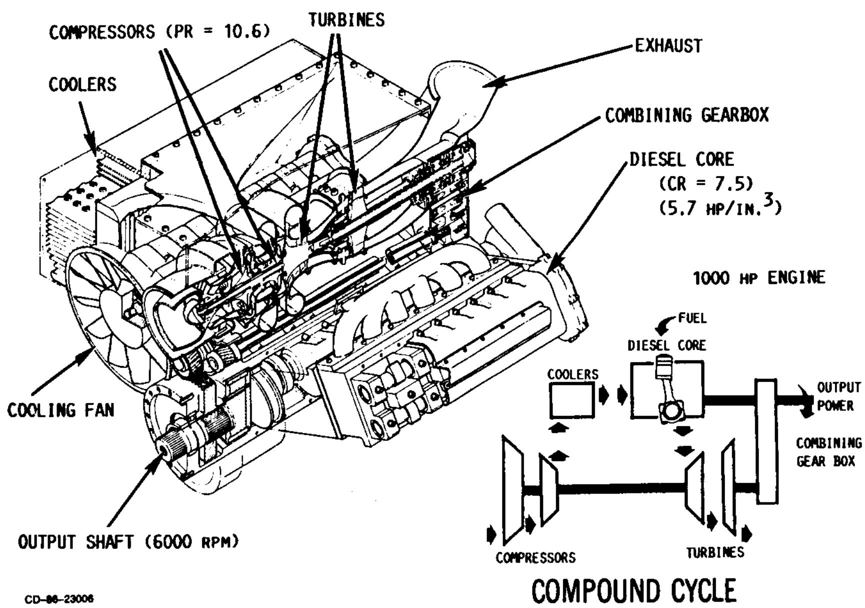

FIGURE 4. - CONCEPTUAL CONFIGURATION OF 1000 HP COMPOUND CYCLE ENGINE.

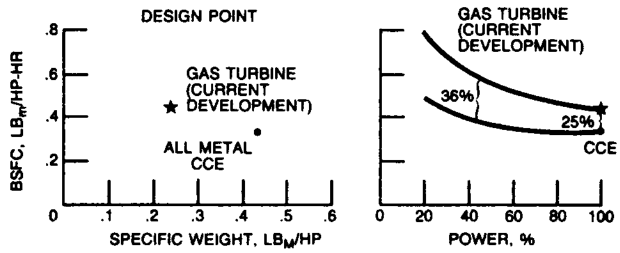

FIGURE 5. - CYCLE PERFORMANCE AND WEIGHT (INCLUDING FUEL AND TANKAGE) COMPARISONS FOR 1000 HP CCE AND GAS TURBINE.

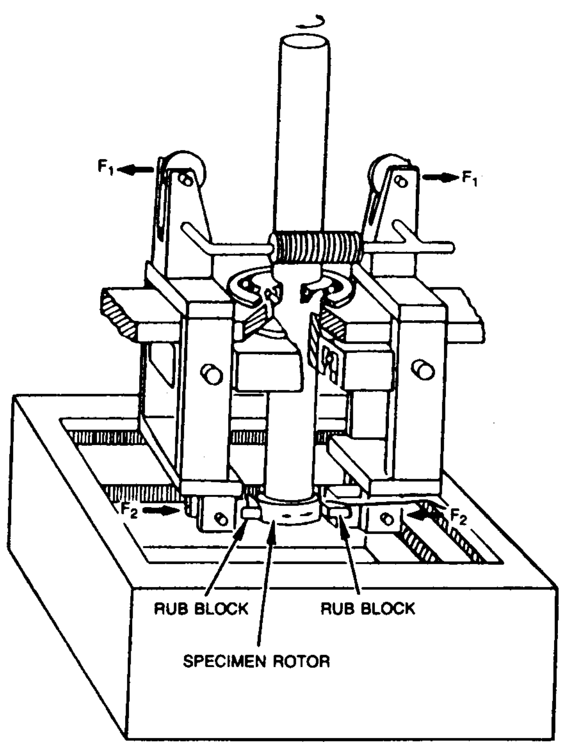

FIGURE 6. - MODIFIED HOHMAN FRICTION AND WEAR TESTER.

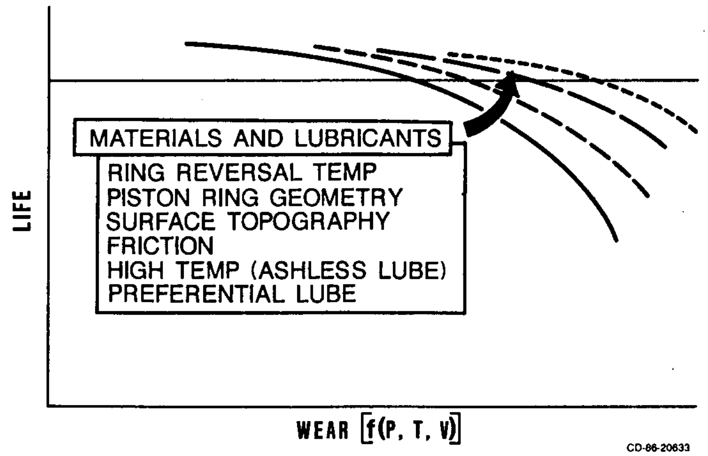

FIGURE 7. - REPRESENTATION OF THE DEPENDENCE OF ENGINE LIFE ON THE CYCLE PARAMETERS (CYLINDER PRESSURE AND TEMPERATURE, AND PISTON VELOCITY) AND TRIBOLOGY.

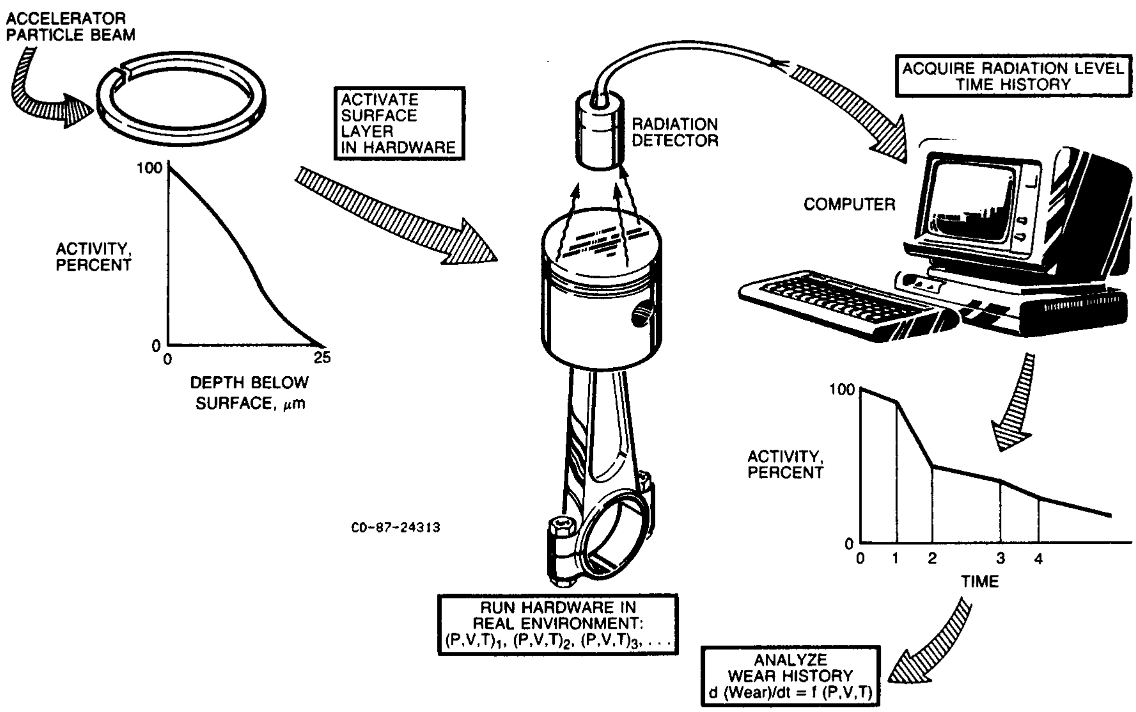

FIGURE 8. - USE OF RADIONUCLIDES DETECTION FOR IN-SITU MEASUREMENT OF COMPONENT WEAR.

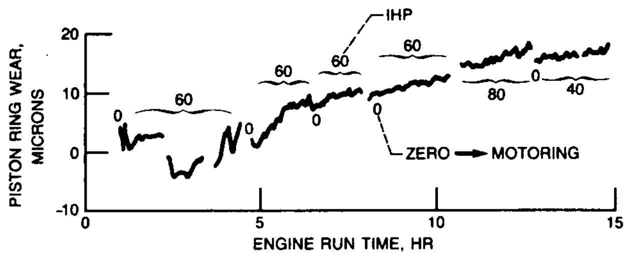

FIGURE 9. - REPRESENTATIVE IN-SITU RING WEAR DATA FROM SINGLE CYLINDER, LOOP SCAVENGED HARDWARE. ENGINE SPEED 6000 RPM, INLET TEMPERATURE 300 °F.

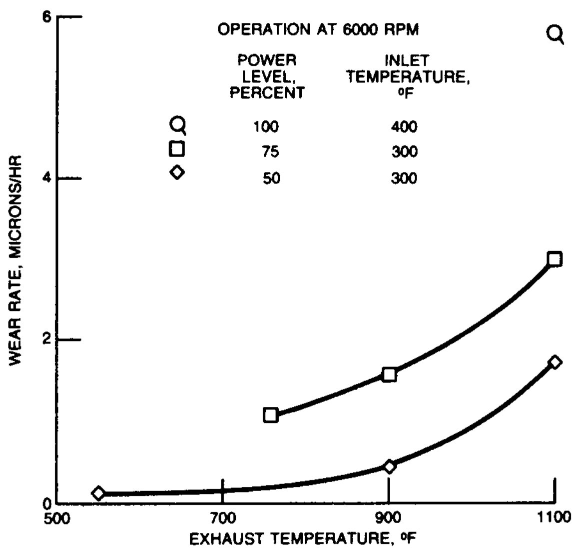

FIGURE 10. - VARIATION OF RING WEAR RATE WITH EXHAUST TEMPERATURE AND POWER LEVEL ON SINGLE CYLINDER, LOOP SCAVENGED HARDWARE. (KOPPERS K1008/K28 PISTON RING ON NITRIDED NITRALLOY LINER.)

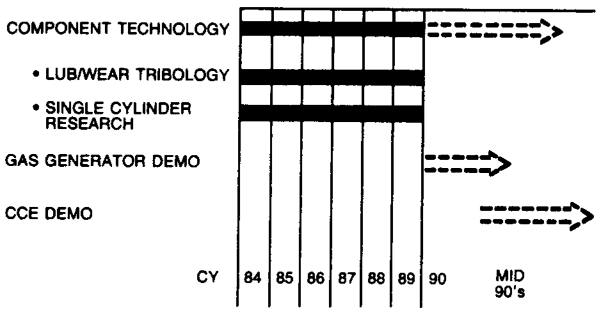

FIGURE 11. - COMPOUND CYCLE ENGINE PROGRAM SCHEDULE.